2. ASTROPHYSICAL CONSTANTS AND PARAMETERS

Table 2.1. Revised May 2008 by E. Bergren and D.E. Groom (LBNL). The figures in parentheses after some values give the one standard deviation uncertainties in the last digit(s). Physical constants are from Ref. 1. While every effort has been made to obtain the most accurate current values of the listed quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference. The values and uncertainties for the cosmological parameters depend on the exact data sets, priors, and basis parameters used in the fit. Many of the parameters reported in this table are derived parameters or have non-Gaussian likelihoods. The quoted errors may be highly correlated with those of other parameters, so care must be taken in propagating them. Unless otherwise specified, cosmological parameters are best fits of a spatially-flat ΛCDM cosmology with a power-law initial spectrum to WMAP 3-year data alone [2]. For more information see Ref. 3 and the original papers.

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	$299\,792\,458$ m s^{-1}	exact[4]
Newtonian gravitational constant	G_N	$6.674\,3(7) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[1]
Planck mass	$\sqrt{\hbar c/G_N}$	$1.220\,89(6) \times 10^{19}$ GeV/c^2	[1]
		$= 2.176\,44(11) \times 10^{-8}$ kg	
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.616\,24(8) \times 10^{-35}$ m	[1]
standard gravitational acceleration	g_N	$9.806\,65$ m s^{-2}	exact[1]
jansky (flux density)	Jy	10^{-26} W m^{-2} Hz^{-1}	definition
tropical year (equinox to equinox) (2007)	yr	$31\,556\,925.2$ s $\approx \pi \times 10^7$ s	[5]
sidereal year (fixed star to fixed star) (2007)		$31\,558\,149.8$ s $\approx \pi \times 10^7$ s	[5]
mean sidereal day (2007) (time between vernal equinox transits)		$23^{\rm h}\,56^{\rm m}\,04^{\rm s}.090\,53$	[5]
astronomical unit	AU, A	$149\,597\,870\,700(3)$ m	[6]
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,6 \times 10^{16}$ m $= 3.262\ldots$ ly	[7]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,053\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,077\,0(2)$ km	[8]
Solar mass	$M_\odot$	$1.988\,4(2) \times 10^{30}$ kg	[9]
Solar equatorial radius	$R_\odot$	$6.9551(3) \times 10^8$ m	[10]
Solar luminosity	$L_\odot$	$3.842\,7(1\,4) \times 10^{26}$ W	[11]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,055\,881$ mm	[12]
Earth mass	$M_\oplus$	$5.972\,2(6) \times 10^{24}$ kg	[13]
Earth mean equatorial radius	$R_\oplus$	$6.378\,137 \times 10^6$ m	[5]
luminosity conversion (deprecated)	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_{\rm bol}}$ W	[14]
		($M_{\rm bol}$ = absolute bolometric magnitude	
		= bolometric magnitude at 10 pc)	
flux conversion (deprecated)	$\mathscr{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\,m_{\rm bol}}$ W m^{-2}	from above
		($m_{\rm bol}$ = apparent bolometric magnitude)	
ABsolute monochromatic magnitude	AB	$-2.5\log_{10} f_\nu - 56.10$ (for f_ν in W m^{-2} Hz^{-1})	[15]
		$= -2.5\log_{10} f_\nu + 8.90$ (for f_ν in Jy)	
Solar velocity around center of Galaxy	Θ_0	$220(20)$ km s^{-1}	[16]
Solar distance from Galactic center	R_0	$8.0(5)$ kpc	[17]
local disk density	$\rho_{\rm disk}$	3–12 $\times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV/c^2 cm^{-3}	[18]
local halo density	$\rho_{\rm halo}$	2–13 $\times 10^{-25}$ g cm^{-3} $\approx$ 0.1–0.7 GeV/c^2cm^{-3}	[19]
present day CMB temperature	T_0	$2.725(1)$ K	[20]
present day CMB dipole amplitude		$3.358(17)$ mK	[21]
Solar velocity with respect to CMB		$369(2)$ km/s	[21]
		towards $(\ell, b) = (263.86(4)^\circ, 48.24(10)^\circ)$	
Local Group velocity with respect to CMB	$v_{\rm LG}$	$627(22)$ km s^{-1}	[22]
		towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ$	
entropy density/Boltzmann constant	s/k	$2\,889.2\,(T/2.725)^3$ cm^{-3}	[14]
number density of CMB photons	n_γ	$410.5(T/2.725)^3$ cm^{-3}	[23]
present day Hubble expansion rate	H_0	$100\,h$ km s^{-1} Mpc^{-1}	
		$= h \times (9.777\,752$ Gyr$)^{-1}$	[24]
present day normalized Hubble expansion rate‡	h	$0.73(3)$	[2,3]
Hubble length	c/H_0	$0.925\,063 \times 10^{26}\,h^{-1}$ m $\approx 1.27 \times 10^{26}$ m	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.852 \times 10^{51}\,h^{-2}$ m^2	
critical density of the Universe	$\rho_{\rm c} = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h^2\,M_\odot$Mpc^{-3}	
		$= 1.878\,35(19) \times 10^{-29}\,h^2$ g cm^{-3}	
		$= 1.053\,68(11) \times 10^{-5}\,h^2$ (GeV/c^2) cm^{-3}	
pressureless matter density of the Universe‡	$\Omega_{\rm m} = \rho_{\rm m}/\rho_{\rm c}$	$0.128(8)\,h^{-2} \approx 0.24$ (WMAP3)	[2,3]
		$0.132(4)\,h^{-2} \Rightarrow 0.27(2)$ (ALL mean)	[2]
baryon density of the Universe‡	$\Omega_{\rm b} = \rho_{\rm b}/\rho_{\rm c}$	$0.0223(7)\,h^{-2} \approx 0.0425$	[2,3]
dark matter density of the universe‡	$\Omega_{\rm dm} = \Omega_{\rm m} - \Omega_{\rm b}$	$0.105(8)\,h^{-2} \approx 0.20$	[2]
dark energy density of the Universe‡	Ω_Λ	$0.73(3)$	[25]
Hubble length	c/H_0	$0.925\,063 \times 10^{26}\,h^{-1}$ m $\approx 1.27 \times 10^{26}$ m	
radiation density of the Universe‡	$\Omega_\gamma = \rho_\gamma/\rho_{\rm c}$	$2.471 \times 10^{-5}(T/2.725)^4\,h^{-2} \approx 4.6 \times 10^{-5}$	[23]
neutrino density of the Universe‡	Ω_ν	$0.0005 < \Omega_\nu h^{-2} < 0.023 \Rightarrow 0.001 < \Omega_\nu < 0.05$	[26]
total energy density of the Universe‡	$\Omega_{\rm tot} = \Omega_{\rm m} + \ldots + \Omega_\Lambda$	$1.011(12)$	[2,27]

Quantity	Symbol, equation	Value	Reference, footnote
baryon-to-photon ratio‡	$\eta = n_{\rm b}/n_\gamma$	$6.12(19) \times 10^{-10}$	[28]
number density of baryons‡	$n_{\rm b}$	$(1.9 \times 10^{-7} < n_{\rm b} < 2.7 \times 10^{-7})\,{\rm cm}^{-3}$ (95% CL)	from η
dark energy equation of state parameter‡	w	$-0.97(7)$	[2]
fluctuation amplitude at $8h^{-1}$ Mpc scale‡	σ_8	0.76(5)	[2,3]
scalar spectral index from power-law fit to data‡	$n_{\rm s}$	0.958(16)	[2,3]
running spectral index slope at $k_0 = 0.05$ Mpc^{-1} ‡	$dn_{\rm s}/d\ln k$	-0.05 ± 0.03	[2,29]
tensor-to-scalar field perturbations ratio at $k_0 = 0.002$ Mpc^{-1} ‡	$r = T/S$	< 0.65 at 95% C.L.	[2,3]
reionization optical depth‡	τ	0.09(3)	[2,3]
age of Universe at reionization ‡	$t_{\rm reion}$	365 Myr	[2,3]
age of the Universe‡	t_0	13.73(15) Gyr	[2]

‡ See caption for caveats.

References:

1. P.J. Mohr, B.N. Taylor, & D.B. Newell, *CODATA Recommended Values of the Fundamental Constants: 2006*, Rev. Mod. Phys. (to be published); `physics.nist.gov/constants`.
2. D.N. Spergel *et al.*, Astrophys. J. Supp. **170**, 377 (2007). Post-deadline WMAP5 values have not been used. In any case, they usually vary no more than 1σ from the WMAP3 values.
3. O. Lahav & A.R. Liddle, "The Cosmological Parameters," this *Review*.
4. B.W. Petley, Nature **303**, 373 (1983).
5. *The Astronomical Almanac for the year 2007*, U.S. Government Printing Office, Washington, and The Stationery Office, London (2005).
6. With the range measurements of the Mars Global Surveyer and Odyssey in 1999–2007 now added to the Viking ranges of 1976-82, the value of the AU is determined to be 149 597 870 700±2 meters. While the AU is approximately equal to the semi-major axis of the Earth's orbit, it is not exactly so. Nor is it exactly the mean earth-sun distance. There are a number of reasons for this: 1) the Earth's orbit is not exactly Keplerian due to relativity and to perturbations from other planets; 2) the adopted value for the Gaussian gravitational constant k is not exactly equal to the earth's mean motion; and 3) the mean distance in a Keplerian orbit is not equal to the semi-major axis; instead, it is $\langle r\rangle = a(1 + e^2/2)$, where e is the eccentricity.
   For an observer far above Earth's orbital plane at rest in the inertial frame of the Solar System, terrestrial clocks would appear to run slower than local clocks because of (a) time dilation from Earth's orbital motion and (b) gravitational redshift at the Earth's surface and in the Sun's potential well. The last contribution is twice as big as the time dilation. The clock rates differ by 1.5 parts in 10^8. These effects complicate the measurement and definition of the AU and $G_N M_\odot$ (Discussion courtesy of Myles Standish, JPL).
7. The distance at which 1 AU subtends 1 arc sec: 1 AU divided by $\pi/648\,000$.
8. Product of $2/c^2$ and the heliocentric gravitational constant $G_N M_\odot = A^3 k^2/86400^2$, where k is the Gaussian gravitational constant, 0.017 202 098 95 (exact) [5]. The value and error for A given in this table are used.
9. Obtained from the heliocentric gravitational constant [5] and G_N [1]. The error is the 100 ppm standard deviation of G_N.
10. T. M. Brown & J. Christensen-Dalsgaard, Astrophys. J. **500**, L195 (1998). Many values for the Solar radius have been published, most of which are consistent with this result.
11. $4\pi\, A^2 \times (1366.4 \pm 0.5)$ W m^{-2} [30]. Assumes isotropic irradiance.
12. Schwarzschild radius of the Sun (above) scaled by the Earth/Sun mass ratio given in Ref. 5.
13. Obtained from the geocentric gravitational constant [5] and G_N [1]. The error is the 100 ppm standard deviation of G_N.
14. E.W. Kolb & M.S. Turner, *The Early Universe*, Addison-Wesley (1990);
    The IAU (Commission 36) has recommended 3.055×10^{28} W for the zero point. Based on newer Solar measurements, the value and significance given in the table seems more appropriate.
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17. M.J. Reid, Annu. Rev. Astron. Astrophys. **31**, 345–372 (1993); M. Shen & Z. Zhu, Chin. Astron. Astrophys. **7**, 120 (2007). In Fig. 2 they present a summary of a dozen modern values for R_0. All but one are within Reid's error band.
18. G. Gilmore, R.F.G. Wyse, & K. Kuijken, Ann. Rev. Astron. Astrophys. **27**, 555 (1989).
19. E.I. Gates, G. Gyuk, & M.S. Turner (Astrophys. J. **449**, L133 (1995)) find the local halo density to be $9.2^{+3.8}_{-3.1} \times 10^{-25}$ g cm^{-3}, but also comment that previously published estimates are in the range 1–10×10^{-25} g cm^{-3}.
    The value 0.3 GeV/c^2 has been taken as "standard" in several papers setting limits on WIMP mass limits, *e.g.* in M. Mori *et al.*, Phys. Lett. **B289**, 463 (1992).
20. J. Mather *et al.*, Astrophys. J. **512**, 511 (1999). This paper gives $T_0 = (2.725 \pm 0.002)$ K at 95%CL. We take 0.001 as the one-standard deviation uncertainty.
21. G. Hinshaw, *et al.*, Astrophys. J. Supp. **170**, 288 (2007).
22. D. Scott & G.F. Smoot, "Cosmic Microwave Background," this *Review*.
23. $n_\gamma = \dfrac{2\zeta(3)}{\pi^2}\left(\dfrac{kT}{\hbar c}\right)^3$ and $\rho_\gamma = \dfrac{\pi^2}{15}\dfrac{(kT)^4}{(\hbar c)^3}$.
24. Conversion using length of sidereal year.
25. Ω_Λ from fits to various data sets is given in Table 12 in Ref. 2. The (meaningless) weighted average from the not-independent data sets is 0.727 ± 0.012. This is almost the WMAP + SDSS LRG fit, which we quote with a 50% more conservative error. The extended error band includes results obtained with all of the data sets.
26. The lower limit follows from neutrino mixing results combined with the assumptions that there are three light neutrinos ($m < 45$ GeV) and that the lightest neutrino is substantially less massive than the others. Limits set from analyses of WMAP, large-scale structure, and other data are in the $\Omega_\nu < 0.02$ range. If the limit obtained from tritium decay experiments ($m_\nu < 2$ eV) is taken seriously, then one can only conclude that $\Omega_\nu < 0.1$.
27. From WMAP 3-year + SNLS data. WMAP 3-year data plus the HST Key Project constraint on H_0 implies $\Omega_{\rm tot} = 1.014 \pm 0.017$ [2].
28. Calculated from ρ_c, $\Omega_{\rm b}$, and n_γ.
29. From WMAP 3-year data alone, assuming no tensors. If other data are included, results from -0.058 to -0.066 are obtained. Inclusion of tensors in the model results in values from -0.082 to -0.090 [2].
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